J. Great Lakes Res. 10(1):28–37
Internat. Assoc. Great Lakes Res., 1984

ECOLOGICAL SIGNIFICANCE OF UPWELLING EVENTS IN LAKE ONTARIO

G. D. Haffner[1], M. L. Yallop, P. D. N. Hebert, and M. Griffiths[2]
Great Lakes Institute
University of Windsor
Windsor, Ontario N9B 3P4

ABSTRACT. Upwelling events in Lake Ontario were studied to determine (1) their significance as mechanisms to provide nutrients from the hypolimnion to the epilimnion and (2) their impact on resident plankton communities of the nearshore zone. It was concluded that such events did not result in sufficient mixing to recharge nutrient stocks of these areas. Upwellings were characterized as being temporal displacements of nearshore water masses which returned at the end of each event. Plankton communities of the nearshore area were displaced with the water mass and therefore received little or no benefit from the upwelled nutrient rich hypolimnetic waters. Evidence is provided to suggest that diatom species such as Asterionella formosa *Hass and* Fragilaria crotonensis *Kitton were able to grow in the upwelled hypolimnetic water, and upwellings might be a mechanism to inoculate these species into the epilimnion of deep lakes prior to the autumn overturn. Upwelling events also caused rapid shifts in the species composition of zooplankton communities. Such shifts were particularly pronounced within 1 km of the shoreline.*

INTRODUCTION

The coastal zone of Lake Ontario is a physically dynamic system (Csanady 1972) strongly influenced by meteorological events (Blanton 1974). Retention times and resultant chemical gradients of the nearshore water mass are determined by inshore-offshore exchanges (Palmer 1972). Such processes have been demonstrated to affect the size and duration of phytoplankton growths (Haffner *et al.* 1982). Major physical perturbations of the thermal structure of the nearshore zone are usually associated with upwelling events of variable duration and intensity. Despite the high frequency of upwelling events in the Great Lakes, there have been few studies as to the ecological significance of these processes. As Lake Ontario is subjected to prevailing westerly winds, upwelling events are common phenomena along the northwest nearshore zone (Lee 1972). El-Shaarawi and Kwiatkowski (1977) reported that the coldest annual mean surface water temperatures were found in the northwest nearshore zone, and that water temperature was progressively warmer eastwardly and southwardly from this location. Sweers (1969) has shown that the near-Toronto shoreline is the region of most frequent upwelling as indicated by water intake temperature records. Considering the prominence of upwellings in this area, it is important to resolve the ecological significance of these events.

In marine systems upwellings are associated with areas of increased primary productivity as a result of nutrient enrichment. Little is known, however, of the influence of upwelling events on plankton communities of smaller aquatic systems. In Lake Ontario Stadlemann and Fraser (1974) concluded that nutrient regeneration processes controlled production in the epilimnion, but they were unable to determine the relative importance of the various physical processes influencing nutrient regeneration. As upwelling events are more prominent in the late summer period when available nutrients have usually been depleted, it seems on *a priori* grounds that these events might increase rates of primary productivity.

[1]Present Address: Water Quality Branch, Place Vincent Massey, 351 St. Joseph Blvd., Hull, Quebec K1A 0E7.

[2]Ontario Ministry of the Environment, 135 St. Clair Avenue West, Toronto, Ontario M4V 1P5.

Biological effects of upwelling events in lakes have been previously observed. Skabitschewsky (1929, cited by Hutchinson 1967) found there was an increase in populations of *Melosira spp.* associated with an upwelling event in Lake Baikal. In Lake Michigan, Yaguchi (1977) reported that benthic algal species became more abundant during upwelling periods. These observations suggest upwellings, particularly in the late summer, not only act as nutrient replenishment mechanisms (Shelske *et al.* 1971) but also as a source for inocula of cells from which the autumnal maxima may be derived.

Upwellings in the Great Lakes have also been discussed by Church (1942), Schelske *et al.* (1971), and Gachter *et al.* (1974). Gachter *et al.* (1974) concluded that associated decreases in primary productivity were a result of the short duration of the events. Harris *et al.* (1980) observed an inverse relationship between the variability of the ratio of the euphotic depth : mixing depth as compared with measured rates of primary productivity in Lake Ontario, thereby supporting the conclusions of Gachter *et al.* (1974).

During 1980 a joint study on the effects of upwelling events on the trophic status of the nearshore zone of Lake Ontario was performed by the Ontario Ministry of the Environment and the Great Lakes Institute of the University of Windsor. Particular emphasis was given to determining the response of phytoplankton and zooplankton populations to these events, and to identify the effects of upwellings on community structure. Previous workers (e.g., Michalski 1969) have noted a lack of community organization in the phytoplankton assemblage of the area, and it is hypothesized that physical events such as upwellings can be a major factor regulating plankton community structure in the northwest nearshore zone of Lake Ontario.

METHODS

A transect northeast of Toronto consisting of three stations (E1, E2, and E3) was sampled (Fig. 1). Stations on the transect were located at 0.8 km, 2.4 km, and 6.0 km from shore, and had respective depths of 8.0 m, 16.0 m, and 50.0 m. Samples were collected throughout the water column at each station as indicated in Figure 1. Between stations E2 and E3, two continuously recording thermisters were moored at 5 m and 20 m depth in order to determine the frequency and duration of upwelling events.

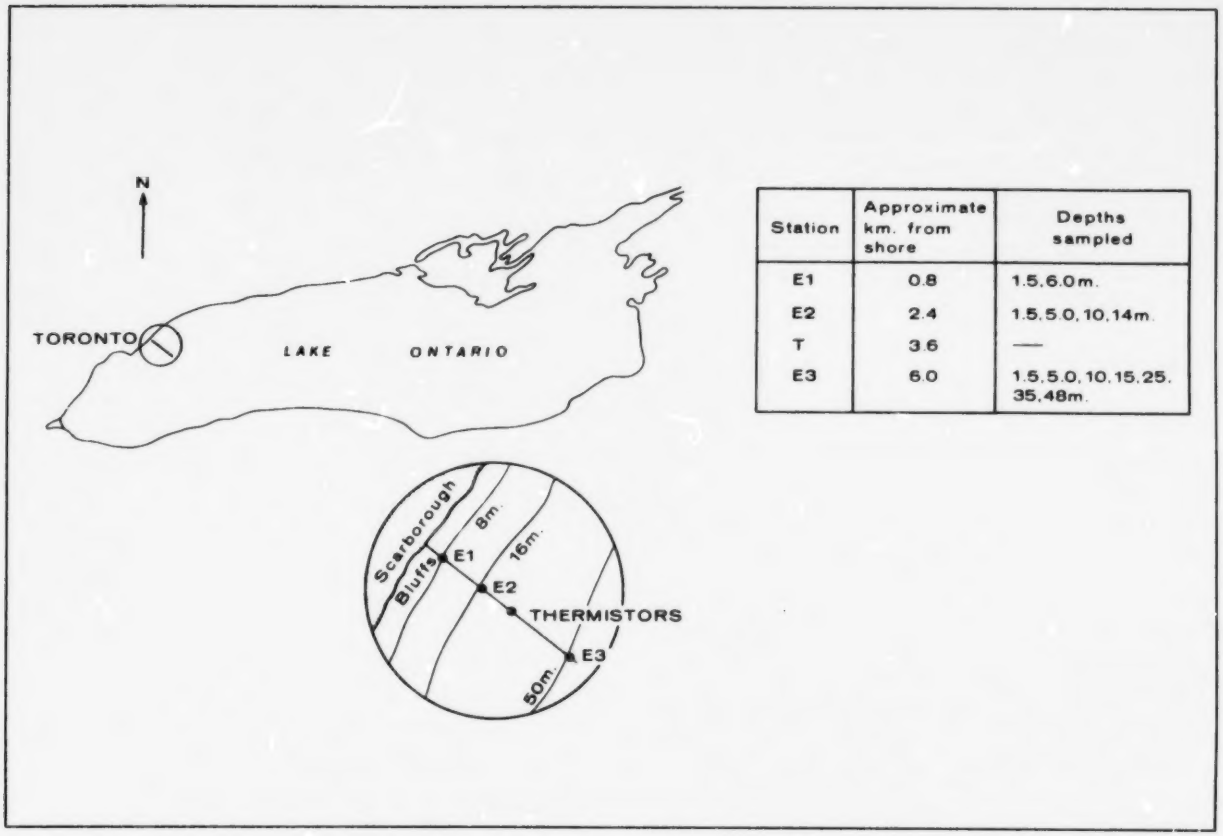
Samples were collected using a Kemmerer sampler weekly from April to November 1980, and analyzed for total phosphorus, silica, and nitrate plus nitrite as described by the Ontario Ministry of the Environment (M.O.E. 1977). Subsamples, fixed with Lugol's iodine, were obtained for determining phytoplankton composition and abundance using the Utermohl technique with split sedimentation tubes (Evans 1972) and the counting procedures outlined by Lund *et al.* (1958).

Zooplankton were sampled at each station using a 30-L Schindler-Patalas plankton chamber with a 64-μm mesh. For enumeration each sample was concentrated to a volume of 10 to 15 mL from which a primary subsample was obtained. Large zooplankters were removed and ethanol was added to the primary subsample to bring it to a known volume of 10 to 15 mL. This latter volume was further subsampled, with one subsample being placed into each of two Sedgewick-Rafter settling chambers for enumeration of small zooplankters. The size of the primary subsample was determined by the abundance of large zooplankters (all cladocera excluding *Bosmina*, adult copepods, and late copepodite stages). The actual volume settled was determined by rotifer abundance. Cladocerans were identified by reference to Edmondson *et al.* (1959), and the copepods were identified according to Smith and Fernando (1978) and Edmondson *et al.* (1959). Rotifers were identified using Stemberger (1979).

RESULTS

Temperature Profiles

Figure 2 provides a summary of the continuous temperature measurements in the northwest nearshore of Lake Ontario. Fluctuations of temperature observed during May and June were possibly associated with the thermal bar formation (Rodgers 1965) and local point source input rather than being representative of upwellings. In July there was a definite upwelling event of about 10 days duration. This was followed by two minor upwelling events which affected surface temperatures after which a major upwelling event occurred for about 14 days in early September. During this latter period, surface (5 metres) water temperatures declined from 18°C to 6°C within a 48-hour interval. Temperature recordings at 20-m depth had also suggested that incursions of hypolimnetic water into the nearshore zone had occurred as tem-



Station	Approximate km. from shore	Depths sampled
E1	0.8	1.5,6.0m.
E2	2.4	1.5,5.0,10,14m.
T	3.6	—
E3	6.0	1.5,5.0,10,15,25, 35,48m.

FIG. 1. Location of the East Transect and sampling stations (E1, E2, and E3). T marks location of continuous recording thermistors.

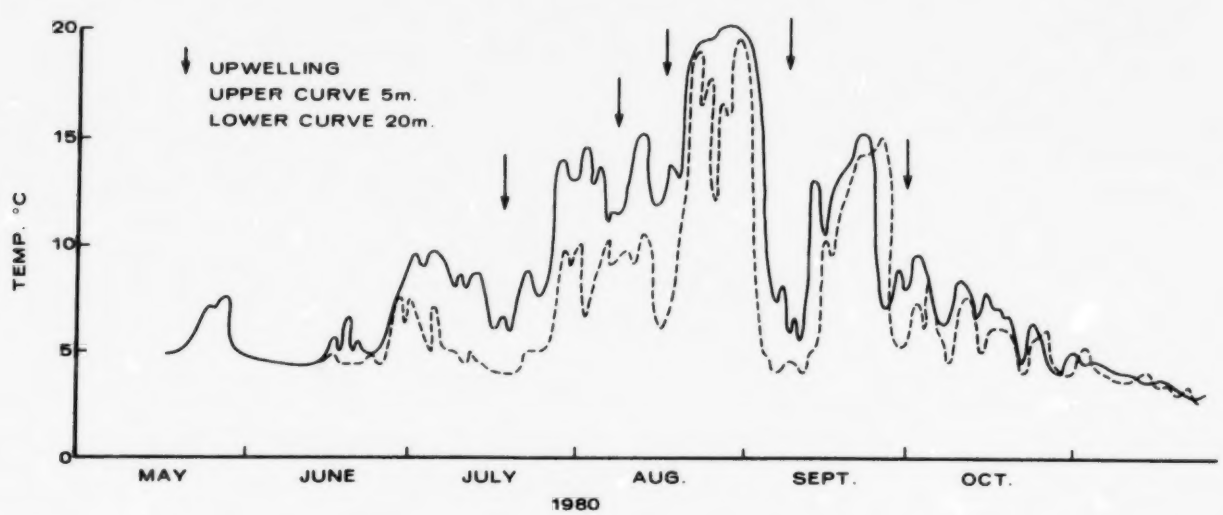


FIG. 2. Plot of continuous temperature recordings (°C) for the East Transect at 5- and 10-m depths. Arrows depict major upwelling events.

peratures declined from 18°C to 4°C. By mid September water temperatures, recorded at 5-m and 20-m depths, returned to 14°C. This common temperature at the two depths indicated that mixing had occurred to a depth of 20 m during the upwelling period.

Continuous temperature recordings illustrate that the early September upwelling event was first observed at the 20-m recording depth as the hypolimnetic waters moved inshore. A sharp decline in temperature at the 20-m station occurred 2 days before the 5-m recording site. Conversely, at the end of the event, the 5-m recordings indicated increasing temperatures before the 20-m site, as the warm epilimnetic waters returned inshore.

Figure 3 represents the thermal structure for stations E1, E2, and E3 as constructed from weekly temperature profiles. By examining these data in association with the continuous temperature recordings, it is evident that the effects of the major upwelling event were confined generally to stations E1 and E2 (within 3 km from shore). There was no definite change in thermal structure at station E3 during the period of the September upwelling. This would suggest that chemical and biological effects would be more pronounced at the two inshore stations, as compared with the relatively stable water column observed at station E3.

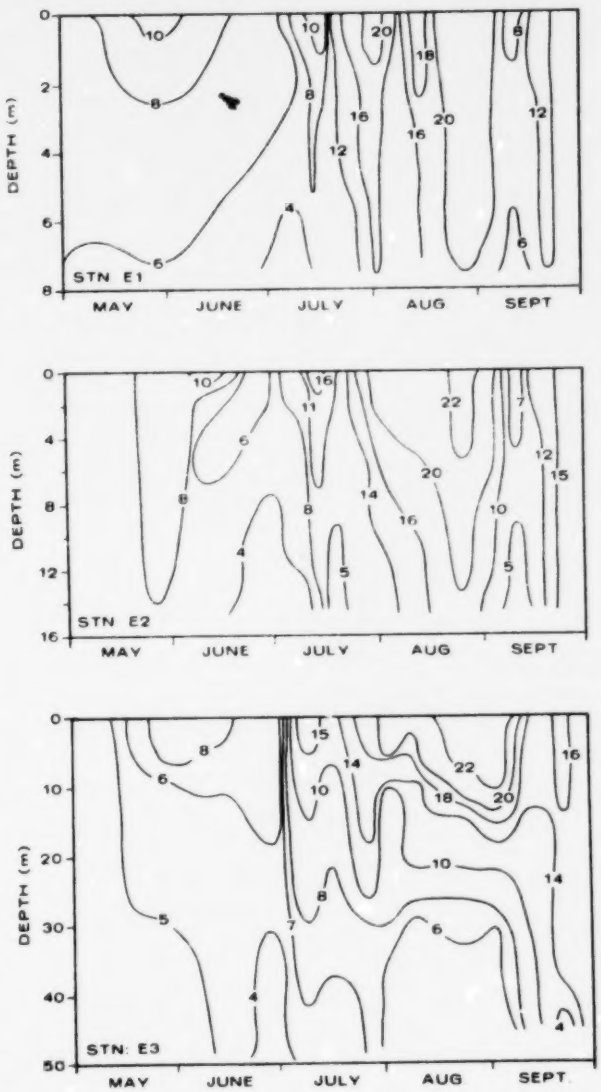


FIG. 3. Spatial and temporal distribution of isotherms at stations E1, E2, and E3, north-west nearshore zone Lake Ontario (note changes in vertical scale).

Water Chemistry

Table 1 summarizes the changes in the mean concentrations of the major nutrients within the euphotic zone. These column-integrated values are used to estimate changes in nutrient stocks on a station-by-station basis. It is apparent that the late summer upwelling did result in minor increases of phosphorus and nitrogen concentrations in surface layers of the nearshore zone. Depth-integrated nutrient concentrations of phosphorus increased only 3to 4 μg P/L, whereas levels of nitrate plus nitrite increased between 140 and 170 NO_3 + NO_2 μg N/L. Depth-integrated concentrations of silica had no discernable change at the two nearshore stations (E1 and E2), although the offshore station (E3) had an increase of 30 μgSi/L.

The data in Table 1 also illustrate that in early September the upwelling had greatly increased NO_3 + NO_2 concentrations in the nearshore zone to well over 200 μg/L. As levels of NO_3 + NO_2 had declined from a spring maximum over 300 μg N/L to a summer minimum below 100 μg/L, the upwelling event did recharge the late summer nitrogen stock of the nearshore zone.

During the early part of the upwelling, levels of total phosphorus and silica actually declined (except at station E3). Phosphorus loadings from nearby municipalities had raised phosphorus concentrations in the nearshore zone over those of the hypolimnetic water. Silica levels in the nearshore zone might have been elevated by local tributaries,

TABLE 1. Changes in mean water column nutrient concentrations during the late summer upwelling, Lake Ontario, 1980 (μg L⁻¹).

Nutrient	STN	Date 27/08/80	03/09/80	18/09/80	Changes in Concentration
$NO_2 + NO_3$	E1	80	320	250	+ 170
	E2	70	270	210	+ 140
	E3	30	230	170	+ 140
TP	E1	19	17	23	+ 4
	E2	17	12	20	+ 3
	E3	18	16	18	0
Si	E1	250	100	260	+ 10
	E2	160	150	150	-10
	E3	180	510	210	+ 30

although the effects of tributaries in this area might be minimal because only small streams with very minor flows enter this section of the lake. For example, no tributary in this area is considered to be a significant phosphorus source (> 1% of annual TP load to the lake).

Biological Effects

Figure 4 illustrates that increases in chlorophyll *a* were associated with upwellings in mid July and mid August (possible upwellings of a deep chlorophyll peak), although a large decline of integrated chlorophyll *a* concentrations occurred at stations E1, E2, and E3 as the late summer upwelling commenced. Changes in chlorophyll *a* at the three nearshore stations are partially explained by the exchange of the resident water mass with hypolimnetic waters. Total integrated algal volumes, however, did not change to the same extent as the chlorophyll *a* concentrations (Fig. 5). The upwelled waters in the late summer included an inocula of algal cells, particularly diatoms, from the aphotic hypolimnion. These cells would be expected to have low chlorophyll *a* concentrations, and this would be consistent with the observed changes in chlorophyll *a* levels and total algal volumes. There was no evidence, however, as to the existence of a deep chlorophyll layer being upwelled with respect to changes in the composition of the phytoplankton community.

Figure 6 summarizes the average volumes of some of the dominant phytoplankton species during 1980. In the middle of August the dominant species were *Cryptomonas ovata* Ehr., *Tabellaria fenestrata* (Lyngb) Kütz., and *Rhodomonas minuta* Skuja, and the populations of all three species were disrupted during the upwelling period. Algal species such as *Melosira islandica* Mull., *M. granulata* (Ehr) Ralfs, and *Scenedesmus bijuga* (Turp) Lagerheim became common, and other species such as *Asterionella formosa* Hass. and *Fragilaria crotonensis* Kitton. increased in abundance toward the end of the upwelling and continued to grow successfully after the event.

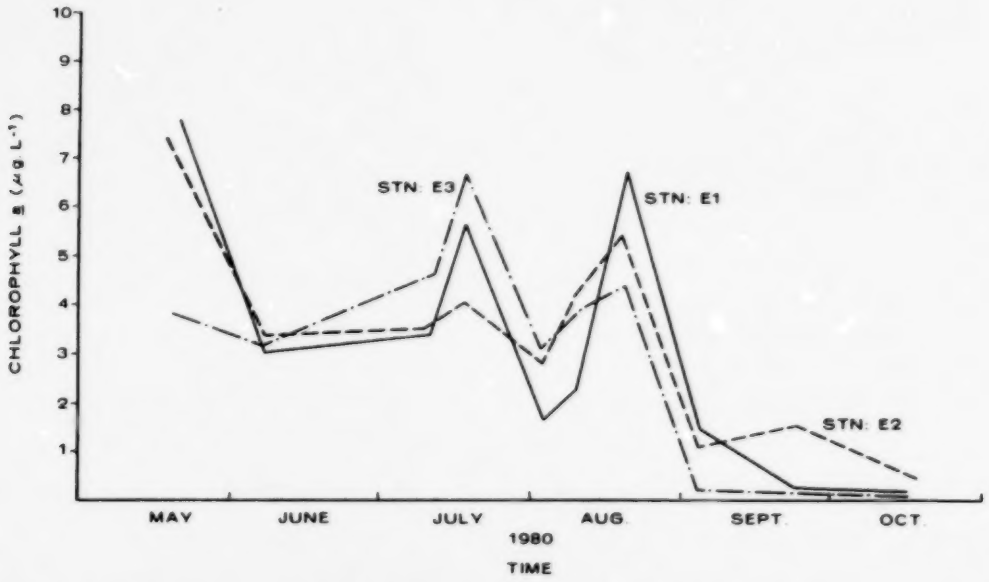


FIG. 4. Column-integrated levels of chlorophyll a (μg/L⁻¹) at stations E1, E2, and E3, 1980.

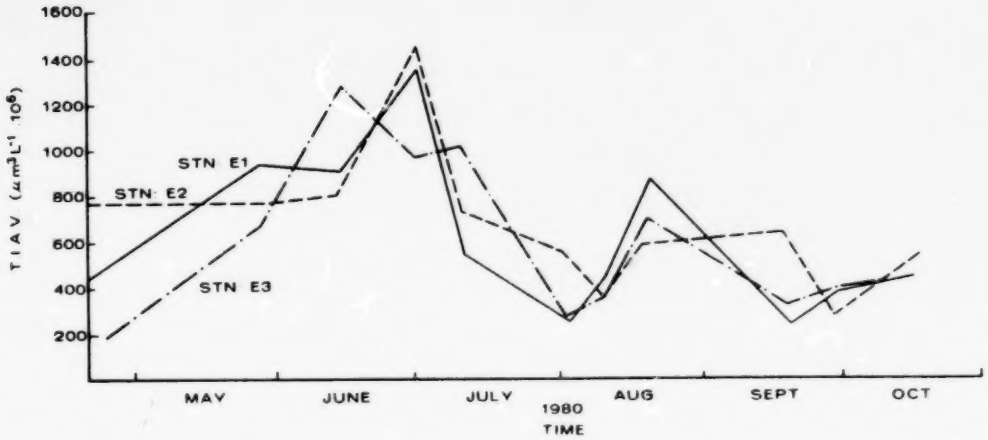


FIG. 5. Column-integrated total algal volumes (T.I.A.V.) (μm³ × 10⁶L⁻¹) at stations E1, E2, and E3, 1980.

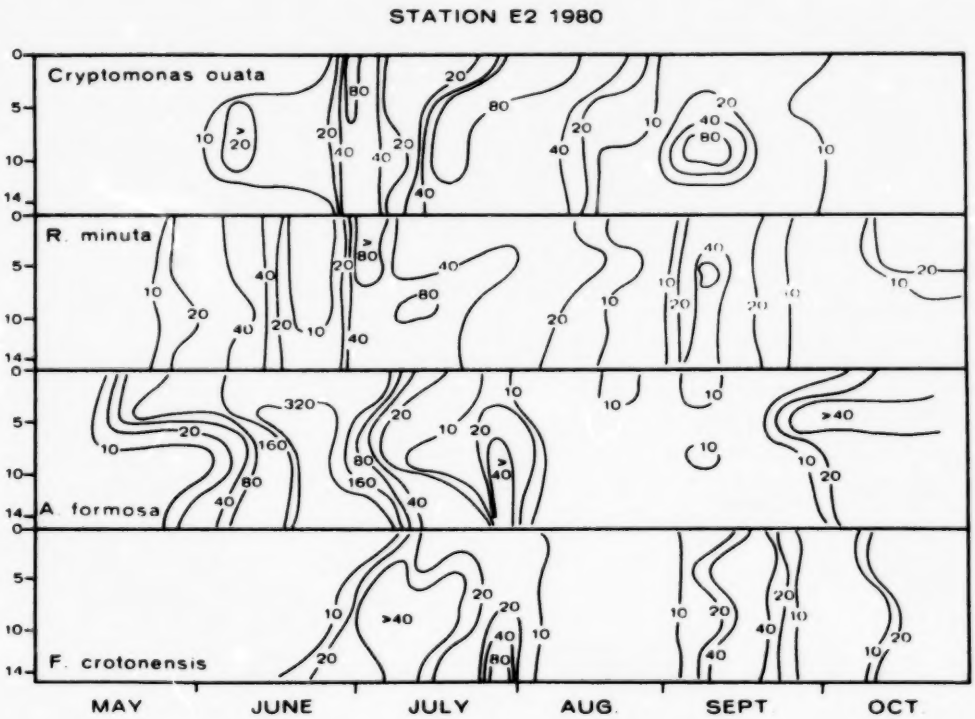


FIG. 6. Changes in the phytoplankton assemblage during the late summer upwelling.

Zooplankton populations of the two nearshore stations (E1, E2) were modified considerably by the late summer upwelling event (Fig. 7). The surveys of zooplankton abundance showed that taxa whose densities peaked with the warm water of late summer showed major density declines during periods of upwelling. The magnitude of these declines were largest at inshore stations, and least evident offshore. For example, Figure 8 illustrates that the average station densities of the rotifer *Polyarthra* spp. oscillated in a similar pattern with nearshore temperatures (Fig. 2), particularly with the periods of the larger upwellings (noted by arrows). At stations E1 and E2 there were four pulses of abundance of *Polyarthra spp.* between July and September 1980 coinciding to periods between upwellings, yet at station E3, *Polyarthra* had a single late summer growth peak. *Keratella spp.* (Fig. 9) illustrated the same pattern as *Polyarthra*.

DISCUSSION

The present study suggests that upwelling events have a direct effect on the structure of the nearshore plankton communities. Major effects tend to be short term. For example, the decline in densities of zooplankton species in nearshore areas was transitory, since the populations were restored at the end of the upwelling event with the return of the nearshore waters.

It is probable upwellings are complex exchanges of entire water masses. In nearshore waters, upwelling results in the displacement of water masses with their resident plankton communities. Few members of the indigenous phytoplankton community would be remaining to take advantage of any nutrient enrichment of the nearshore habitat. Species that were inoculated into the nearshore because of the upwelling tended to have large cell

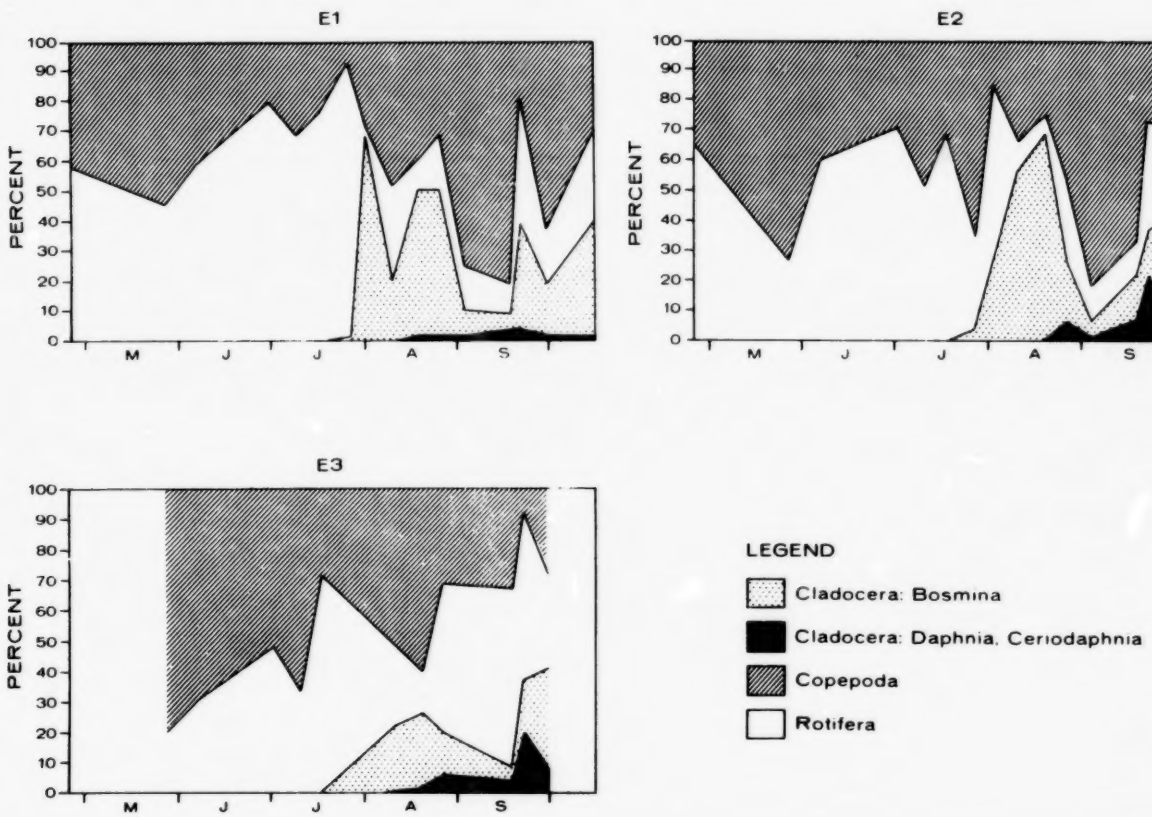


FIG. 7. Spatial and temporal representaiton of the relative abundance of zooplankton taxa at stations E1, E2, and E3, 1980.

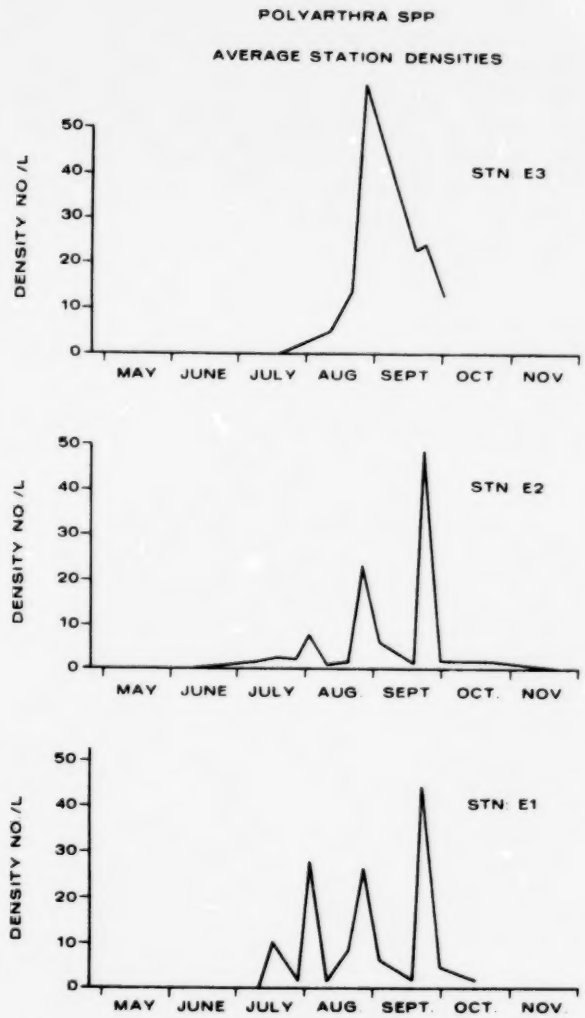


FIG. 8. Average station densities of **Polyarthra** *spp. at stations E1, E2, and E3. Note the number of peaks of abundance of the nearshore stations compared with the single peak of the offshore station.*

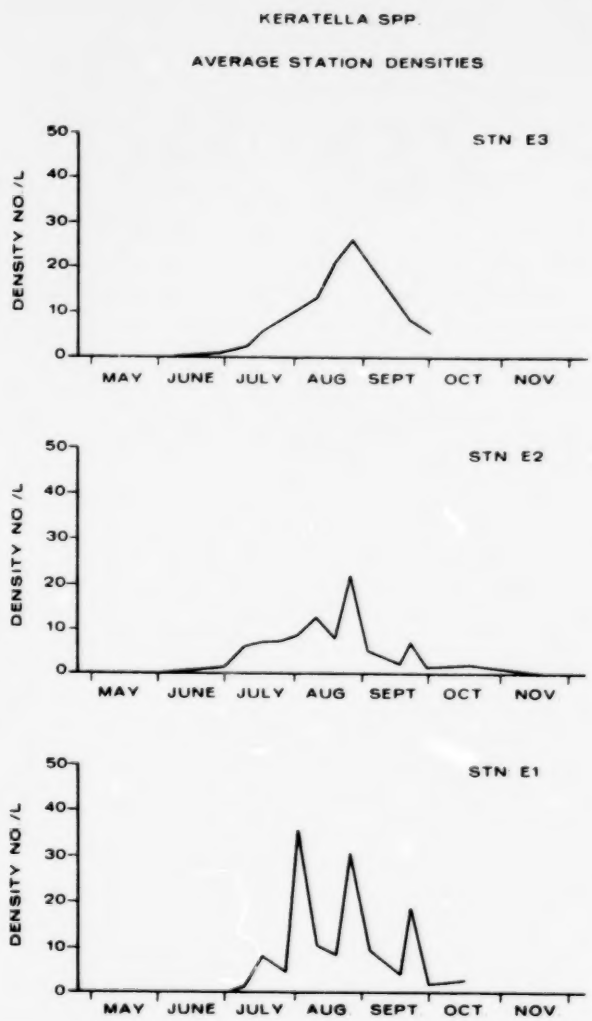


FIG. 9. Average station densities of **Keratella** *spp. at stations E1, E2, and E3. Note the similarity in the multi peaks of abundance in nearshore area with that of* **Polyartha** *spp.*

sizes and, combined with the cold water temperatures, would have slow growth rates. Some of these inoculated species (*Melosira islandica, M. granulata, A. formosa*) formed relatively large populations after the upwelling was completed. These species might well be dependent on upwelling events to return into the euphotic zone before the autumn turnover.

Mixing between the hypolimnetic waters and the nearshore water during the late summer would have been along a shear line between stations E2 and E3 as the water masses moved past each other. Considering the temperature differences of the two water masses, 4°C vs. > 20°C, it is unlikely that much mixing could occur. At the end of the event, surface nearshore waters had only cooled by 4°C (18°C 28 August to 14°C 14 September), again supporting the conclusion that little mixing occurred during the upwelling event.

The water mass which returned nearshore at the end of the upwelling had a plankton assemblage similar to that found before the upwelling event.

This observation also supports the hypothesis that during an upwelling the nearshore waters are displaced into the epilimnion of the open lake, and then are returned with little chemical or biological change.

No productivity measurements were made during the 1980 late summer upwelling, and published works on the effects of upwelling on productivity suggest opposing views. Schelske *et al.* (1971) observed increased cell numbers and productivity during an upwelling in Lake Michigan, while Gachter *et al.* (1974) noted that upwelling decreased biomass and productivity in Lake Ontario. Yaguchi (1977) found increased biomass and reduced productivity during an upwelling in Lake Michigan. Many of the phytoplankton cells introduced into the euphotic zone of the nearshore area during 1980 were observed to have shrunken chromatophores, and it is unlikely such cells would be able to photosynthesize at significant rates. It is possible that the different observations in the literature depend on how much mixing occurred between the water masses. Upwelling in the early summer might result in more mixing of the water masses, as there would be less of a density gradient between the water masses involved. A less stable temperature gradient might, however, shorten the upwelling period in these cases (as observed in Fig. 2). In either early or late summer the ecological significance of the upwelling is possibly minor, as there would be no long-term stimulation of production.

The replacement of water masses by upwellings can explain earlier observations on the plankton communities of the Great Lakes. Munawar and Nauwerck (1971) observed a general tendency for phytoplankton to develop single peak growth patterns in the offshore waters of Lake Ontario, and noted repeated pulses of abundance in the nearshore region. These pulses are probably not periods of active growth, but are exchanges of nearshore and offshore water masses. During 1980 there were four definite upwellings in the northwest nearshore zone of Lake Ontario. This relatively high frequency of upwelling events would isolate the nearshore plankton community from nutrient sources, and would possibly result in considerable "patchiness" of the offshore waters. The excursions of nearshore water masses into the open lake areas could also result in considerable confusion as to the trophic status of the lake, unless there was a sound knowledge of physical processes such as water movement. Such water mass exchanges could explain the results of Stoermer *et al.* (1971), who found "eutrophic" indicator species in the open lake waters of Lake Michigan.

REFERENCES

Blanton, J. O. 1974. Some characteristics of nearshore currents along the north shore of Lake Ontario. *J. Phys. Oceanogr.* 4 415–424.

Church, P. E. 1942. *The annual temperature cycle of Lake Michigan. II. Spring warming and summer stationary periods 1942.* Univ. Chicago, Inst. Meteoral. Misc. Report.

Csanady, G. 1972. A coastal boundary layer in Lake Ontario. I. The spring regime. *J. Phys. Oceanogr.* 2 41–53. II. The summer fall regime. *J. Phys. Oceanogr.* 2 168–176.

Edmondson, W. T., Ward, H. B., and Whipple, G. C. 1959. *Freshwater Biology* 2nd Ed. New York and London: John Wiley and Sons.

El-Shaarawi, A. H., and Kwiatkowski, R. E. 1977. A model to describe the inherent spatial and temporal variability of parameters in Lake Ontario 1974. *J. Great Lakes Res.* 3:177–183.

Evans, J. H. 1972. A modified sedimentation system for counting algae with an inverted microscope. *Hydrobiol.* 40:247–250.

Gachter, R., Vollenweider, R. A., and Glooschenko, W. A. 1974. Seasonal variations of temperatures and nutrients in the surface waters of Lakes Ontario and Erie. *J. Fish. Res. Board Can.* 31:275–290.

Haffner, G. D., Poulton, D. J., Kohli, B. B. 1982. Physical processes and eutrophication. *Wat. Res. Bull.* 18:457–464.

Harris, G. P., Haffner, G. D., and Piccinin, B. B. 1980. Physical variability and phytoplankton communities, II. Primary productivity by phytoplankton in a physically variable environment. *Arch. Hydrobiol.* 88:393–425.

Hutchinson, G. E. 1957. *A Treatise on Limnology*, Vol. I. New York, Chichester, Brisbane, Toronto: John Wiley and Sons.

Lee, A. H. 1972. Regional characteristics of the thermal properties of Lake Ontario. In *Proc. 15th Conf. Great Lakes Res.*, pp. 625–634. Internat. Assoc. Great Lakes Res.

Lund, J. W. G., Kipling, C., and LeCren, E. D. 1958. The inverted microscope method of estimating algal numbers, and the statistical basis of estimation by counting. *Hydrobiol.* II: 143–170.

Michalski, M. F. P. 1969. Investigations of daily variations in chemical, bacteriological and biological parameters of two Lake Ontario locations near Toronto. Part III Biology. In *Proceedings 12th Conf. Great Lakes Res.*, pp. 67–79. Internat. Assoc. Great Lakes Res.

M.O.E. 1977. *Outline of analytical methods. A guide to*

the occurrence, significance, sampling and analysis of chemical parameters in water. Laboratory Services Branch, Ontario Ministry of the Environment.

Munawar, M., and Nauwerck, A. 1971. The composition and horizontal distribution of phytoplankton in Lake Ontario during the year 1970. In *Proc. 14th Conf. Great Lakes Res.*, pp. 69–78. Internat. Assoc. Great Lakes Res.

Palmer, M. D. 1972. Some chemical and physical relationships in Lake Ontario. *Water Res.* 6:843–858.

Rodgers, G. K. 1965. The thermal bar in the Laurentian Great lakes. In *Proc. 8th Conf. Great Lakes Res.*, pp. 358–363. Univ. Mich. Great Lakes Research Div. Pub. 13.

Schelske, C. L., Stoermer, E. F., and Feldt, L. E. 1971. Nutrients, phytoplankton productivity and species composition as influenced by upwelling in Lake Michigan. In *Proc. 14th Conf. Great Lakes Res.*, pp. 102–113. Internat. Assoc. Great Lakes Res.

Smith, K., and Fernando, C. H. 1978. *A guide to the freshwater calanoid and cyclopoid copepod crustacea of Ontario*. University of Waterloo Biology Series, Number 18.

Stadlemann, P., and Fraser, A. 1974. Phosphorus and nitrogen cycle on a transect in Lake Ontario during the International Field Year 1972–1973 (IFYGL). In *Proc. 17th Conf. Great Lakes Res.*, pp. 92–108. Internat. Assoc. Great Lakes Res.

Stemberger, R. S. 1979. *A guide to rotifers of the Laurentian Great Lakes*. USEPA Ecol. Res. Ser. EPA-600/4-79-021.

Stoermer, E. F., Schelske, C. L., and Feldt, L. E. 1971. Phytoplankton assemblage differences at inshore versus offshore stations in Lake Michigan and their effects in nutrient enrichment experiments. In *Proc. 14th Conf. Great Lakes Res.*, pp. 114–118. Internat. Assoc. Great Lakes Res.

Sweers, H. E. 1969. *Structure, dynamics and chemistry of Lake Ontario. Investigations based on monitor cruises in 1966 and 1967*. Man. Rpt. Ser. No. 10. Mar. Sci. Branch. Department of Energy Mines and Resources, Ottawa, Canada.

Yaguchi, E. M. 1977. Nutrients and productivity as indicators of thermal effluents-upwelling interactions in Lake Ontario. *J. Great Lakes Res.* 3:57–64.